Channel Movement of Meandering Indiana Streams

GEOLOGICAL SURVEY PROFESSIONAL PAPER 732-A

Prepared in cooperation with the State of Indiana Department of Natural Resources

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By JAMES F. DANIEL

PHYSIOGRAPHIC AND HYDRAULIC STUDIES OF RIVERS

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CONTENTS

ILLUSTRATIONS

TABLES

CHANNEL MOVEMENT OF MEANDERING INDIANA STREAMS

By James F. Daniel

ABSTRACT

The process of channel movement in a meander system involves rotation and translation of meander loops and an increasing path length. The amount of path-length increase is directly proportional to the impulse supplied by discharge and is inversely proportional to the silt-clay percentage of the material composing the channel perimeter.

Comparable paths have been obtained by standardizing measurements with a sine-generated curve and a moving reference axis. Analysis of previous investigations and time-of-travel data indicates that the discharge effective in channel formation consists of the range beginning just higher than the average and continuing throughout all higher discharges. Of six field sites investigated, three meander systems had path-length increases of sufficient magnitude to correlate with above-average discharge volume, one had no discernible change over a 30-year period, and two had changes which were too small for correlation owing to the short period of time covered by the available data.

Because of the consistency of yearly above-average discharge volumes, it was possible to develop a general relation between path-length increase per thousand cubic-feet-per-second-days per square mile of drainage area above average discharge and the width-depth ratio of the channel. Little progress was made toward defining relationships for rotation and translation.

INTRODUCTION

For many years the planimetric meander form has both intrigued and perplexed geomorphologists. Each investigation has added some facet to the knowledge of meanders. Today, while no one will claim that all the answers are known, the state of knowledge is such that the physical characteristics of meanders can be described in mathematical models with a reasonable degree of accuracy. Laboratory and field investigations, such as the one by Toebes and Sooky (1966), have provided information about the mechanics of flow within a meander, while theoretical investigations, such as those by Langbein and Leopold (1966) and Scheidegger and Langbein (1966), have delved into statistical concepts related to the development of meanders.

Much information is available about why meanders begin and about meanders in a static situation. However, a meander is not a static entity. It is dynamic in every respect. Valuable farmland in the flood plains of meandering streams is lost or changes ownership, and powerplants next to eroding banks require expensive bank stabilization, as do highway bridges and other structures which are in the path of moving, meandering channels. Investigations are needed regarding how, how much, and at what rate meanders move. Relationships need to be developed with which movement of meanders can be predicted. It is to these factors, which are of practical importance after the initiation of meandering, that this report is addressed.

Many persons have provided assistance to the author during this project, especially Richard F. Hadley, U.S. Geological Survey, Denver, Colo., who performed the field reconnaissance and made many suggestions about data collection. This investigation was conducted with financial cooperation by the Indiana Department of Natural Resources, Division of Water, whose personnel also contributed by supplying the field surveys for two of the sites investigated. Most of the personnel of the Indiana District at one time or another aided in the field surveys, often under adverse climatic conditions.

CONCEPTS

It is the thesis of this report that the process of channel movement in a system already in a state of meandering involves rotation and translation of the loops and an increasing path length. Any one or any combination of these forms of movement may occur, depending on the boundary conditions of the loop. Each of the components of movement must be known in order to predict movement. Direction of movement is related to the impulse required to change flow direction, and rate of movement is related to discharge and grain size of the bed and bank material.

MOVEMENT DEFINED

The Sine-Generated Curve

Historically, the meander pattern has been described as either a sine curve defined by amplitude and wavelength or a series of semicircles defined by radius and wavelength. Many authors have correlated these parameters with discharge in an attempt to discover regional or universal relationships between them. Upon cursory examination of a topographic map showing meanders, it is apparent that measurements of their amplitudes, wavelengths, and radii would be very subjective. Each investigator would undoubtedly have a slightly different interpretation of each of these parameters. The result is that there are many slightly different but similar equations relating these parameters in existing literature. The work of Carlston (1965) did much to rectify some of the discrepancies between equations.

Langbein and Leopold (1966) provided a method to remove at least some of the subjectivity from the description of meanders. They showed the best description of a meander loop to be a sine-generated curve described by the equation:

$$\phi=\omega \sin \frac{s}{P} 2\pi \qquad (1)$$

where ϕ=the angle of deviation of a tangent at the end of s from the mean downstream direction.

ω=the maximum angle of deviation of path from the mean downstream direction (usually in degrees).

s=a segment of P (in feet).

and P=the path distance through one wavelength (usually in feet).

By inspection of the example (fig. 1) for the White River near Worthington, it can be readily seen that a sine curve is the best fit for the data of this meander loop. Although a complete wavelength does not exist, the meander is uniquely defined by the parameters ω and P. This method has been used to describe the path length of the concave bank for movement comparison of the meanders under investigation in this report.

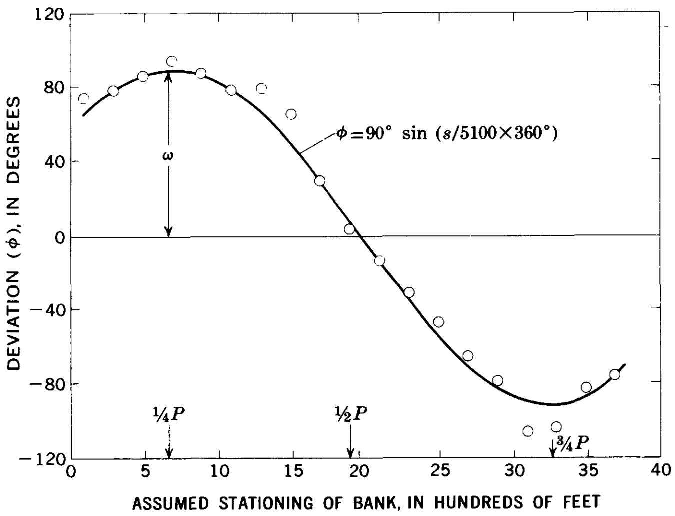

FIGURE 1.—Sine curve of the best fit to data for the White River near Worthington site, July 5, 1937.

Moving Reference Axis

This study was begun using the procedure that cross sections would be surveyed at each site, steel pins would be set within the cross sections, and measurements of erosion and deposition at these pins would be made. After obtaining these movement data, correlations would be made with discharge. This procedure was in fact followed. However, after some insight was gained about the mode of movement, it was found that this type of data had little applicability to the problem under investigation.

For example, figure 2 shows a theoretical meander for two instants in time. At time t_1, the loop is defined by ω_1 and P_1, while at at time t_2, it is defined by ω_2 ($\omega_2 \neq \omega_1$) and P_2 ($P_2 \neq P_1$). If, between t_1 and t_2, measurements of erosion were periodically made at section A, the data obtained from each measurement would represent the end point of different fractions of the total path length. Therefore, any correlation of these data would not represent the movement of a point on the meander loop but would represent the time at which different points on the dynamic loop would reach a fixed reference. The data obtained would have little application to prediction of future movement of this meander or comparison to movement of another meander.

Let us consider, however, the result of using the concepts of a sine-generated curve and a dynamic

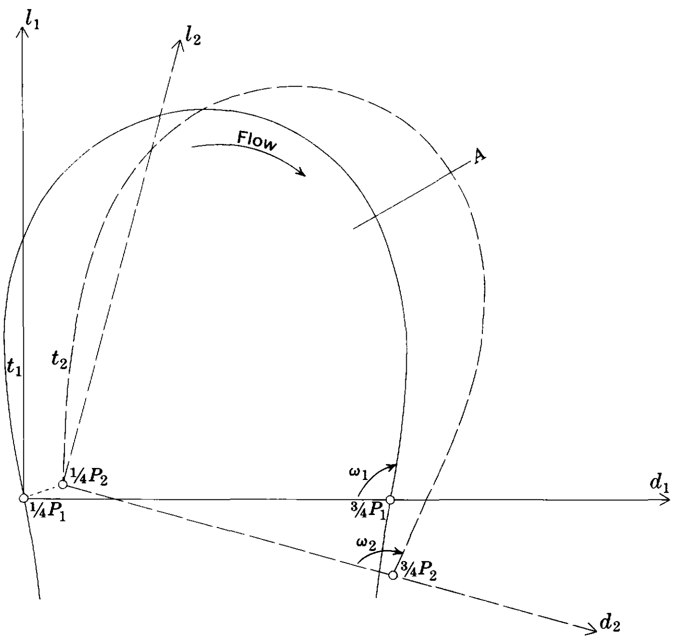

FIGURE 2.—General mechanism of meander loop movement.

system. At time t_1 the meander loop is defined by ω_1 and P_1. Therefore, we can determine the stationing of the maximum deviations of the channel from the mean downstream direction, $\frac{1}{4}P_1$ and $\frac{3}{4}P_1$. The mean downstream direction is the line connecting those points. We can then set our reference axes along this line (labeled d_1) and perpendicular to it (labeled l_1) with the origin at $\frac{1}{4}P_1$. At time t_2 the same operations are performed, resulting in coordinate axes d_2 and l_2 and points $\frac{1}{4}P_2$ and $\frac{3}{4}P_2$. We can then define the movement of the meander by measurements of the length and direction of the line from $\frac{1}{4}P_1$ to $\frac{1}{4}P_2$, the rotation of the axes, and the change of ω and P. These measurements of equivalent points and parameters of a developing loop would have value in prediction of future movement and comparison with different loops.

We have, in effect, made our measurements with reference axes which translate and rotate with time. This concept leads to a number of methods by which meander development could be described, and the method used in this report will be described in a subsequent section.

Observed Modes of Movement

Implied in the construction of figure 2 is the idea that the meander is evolving by two mechanisms. At time t_2, $P_2 \neq P_1$, $\omega_2 \neq \omega_1$, and $d_2 \neq d_1$. This is one mode of change which has been observed for the meanders under study for this investigation. Observed movements constitute five general classes of expansion (increasing P) and rotation ($d_2 \neq d_1$), depending on the boundary conditions of the loop. One class of movement is shown in figure 2 and the other four general classes are illustrated in figure 3. These five modes are applicable to vertically stable (little or no aggradation or degradation), alluvial channels investigated in this study. Channels incised in bedrock would have the meander pattern imposed by the stream when degradation began. Because of the abrasive effect of bedload, their mode of movement is basically vertical rather than lateral.

The concept of increasing path length (ΔP), a contributing factor to the movements shown in figure 3, was inferred by Langbein and Leopold (1966, p. H2):

> In the context of the whole river system, a meandering segment, often but not always concentrated in downstream rather than upstream portions of the system, tends to provide greater concavity by lengthening the downstream portion of the profile. By increasing the concavity of the profile, the product of discharge and slope, or power per unit length becomes more uniform along a stream that increases in flow downstream. Thus the meander decreases the variance of power per unit length * * *.

The conclusion is reached that meanders provide a greater path length which makes energy dissipation more uniform. It is reasonable to extend this conclusion to say that, unrestricted, the path length would continue to increase until energy dissipation is uniform. In the field, natural cutoffs or chuting (Friedkin, 1945) would occur before uniform energy dissipation was achieved. Therefore, in the dynamic system, increasing path length is a requirement.

Figure 3 illustrates an extension of this concept. In figure 3*A*, points a_1 and a_1' are essentially fixed. Such a condition exists when dense vegetation or "clay plugs" restrict movement of the banks at these points. In this situation, erosion results simply in a path-length increase. In figure 3*B*, point a_1' is fixed while a_1 is not, and in figure 3*C* the reverse is true. In either situation, the two mechanisms, change of downstream direction (rotation) and increasing path length, are more equal in effect. Figure 3*D* shows a loop whose condition is very near dynamic equilibrium in a uniformly erodible medium. Such a condition is approached in laboratory experiments (Friedkin, 1945) in which the whole meander system tends to translate downstream.

Not shown are conditions which might result if the less erodible parts of the loop constituted other segments of the loop. Many possible combinations are obvious. The significant point is that a meander system works toward equal energy dissipation by

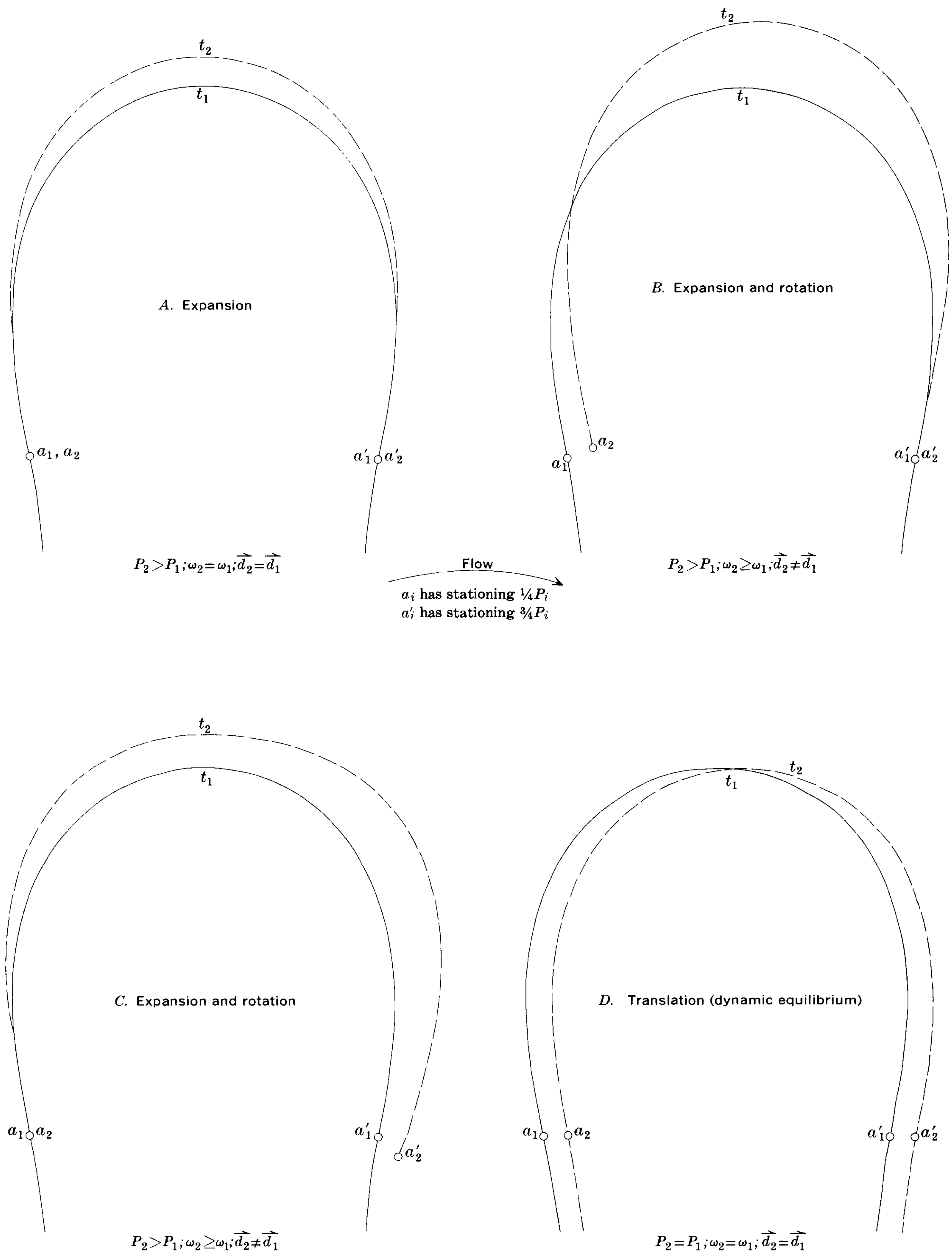

FIGURE 3.—Effects of stationary and (or) translating end points on meander loop movement.

increasing the path length, and where erosion rates within a loop differ greatly, rotation also occurs.

These mechanisms of movement should have application to all forms of free meanders when they are viewed throughout a period of time. Boundary conditions at the end points of and within each loop can result in the dominance of any single mechanism of increasing path length, rotation, or translation, but the usual condition would be some combination of the three.

THEORETICAL MECHANICS OF MOVEMENT

That meandering is a stochastic process has been established by previous studies. One can reasonably expect, however, that cause-effect relationships govern the movement of an individual meander.

Impulse Momentum

Friedkin (1945, p. 11) wrote, "The rate of bank erosion depends upon the force of the water against the banks as well as the toughness of the banks." It is a small step from this idea to the concept of impulse-momentum change, which seems to offer the most reasonable basis for an explanation of movement.

Assume a segment of channel with constant curvature as shown in figure 4. The mean velocity vector of the fluid, which has a discharge of q and flows in the channel between points A and B, can be represented by the unit vector $\mathbf{v}$ which is parallel to a tangent to AB at any point.

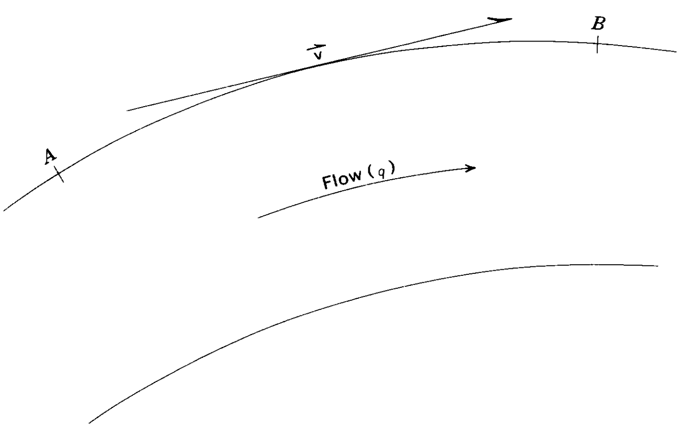

FIGURE 4.—Identification of elements of the momentum concept.

At point A, q has momentum $\rho q \mathbf{v}_A$ and at point B, q has momentum $\rho q \mathbf{v}_B$ where ρ is the density of the fluid. The difference in the two values is the change of momentum in the intervening reach and ideally is equal to the force applied by the bank to the water. Of prime interest, however, is the force applied by the water to the bank—that is, the impulse of the water on the bank.

The mechanism of bank movement can be explained in terms of the applied impulse on the bank and the resulting momentum of dislodged bank material. The following equation expresses this mechanism:

$$\int_{t_A}^{t_B} F_q dt = (mv_B)_b - (mv_A)_b \qquad (2)$$

where F_q is the force supplied by the water, t_A and t_B are the times at which q pases points A and B, $(mv_A)_b$ is the product of mass and velocity of the bank at t_A, and $(mv_B)_b$ is the same product at t_B. The bank material between A and B has no momentum at t_A. However, in an erodible material the impulse dislodges individual grains of bank material which are moved by the flow and do have momentum at t_B. Equation 2 can then be rewritten for the grains affected by q as:

$$\int_{t_A}^{t_B} F_q dt = (m_g v_B)_b \qquad (3)$$

As $AB \rightarrow 0$, equation 3 represents the impulse at a point where the left side of the equation is the force of the fluid on the bank, the time interval of force application has end points t_A and t_B, and the direction of the force is always tangent to the channel. In the real situation this direction of force tends to increase the path length.

The foregoing expression does not take into account the process occurring on the opposite bank where material is being deposited and hence losing momentum. For the streams investigated and for most streams with similar climatic and physical conditions, the channel characteristics are relatively stable; that is, even though meanders move with some rapidity, widths, depths, and width-depth ratios remain fairly constant so that the amount of material deposited very nearly equals the amount of material removed. Therefore, equation 3 is an adequate, albeit gross, means of representing movement of the concave bank if it can be assumed that the force effective in removing bank material is directly proportional to the total flow in the stream, Q. This assumption has been made, and it is the movement of the concave bank which has been analyzed.

The next steps are to put equation 3 in a form more easily analyzed with available data and make the necessary real-world substitutions. For a constant force, equation 3 can be rewritten as:

$$F_q\ (t_B-t_A)=(m_g v_B)_b \qquad (4)$$

Movement is another way of expressing material removed, $(m_g v_B)_b$. Because the direction of force is always toward increasing path length ($\triangle P$), the right side of equation 4 is proportional to $\triangle P$. Force is proportional to Q. Different materials erode at different rates, depending on the cohesiveness of the material. The more cohesive the material the slower it erodes, so $\triangle P$ is inversely proportional to cohesiveness. A convenient measure of cohesiveness is the percentage of silt and clay in a material, M, as defined by Schumm (1960). Substituting in equation 4 results in the relation:

$$\frac{Q\,(t_B-t_A)}{M} \propto \triangle P \qquad (5)$$

This expression lends itself to the use of flow-duration data.

Duration data are compiled in tables listing the number of days for narrow discharge ranges. The product of the number of days for each range (N) and the average discharge of that range can be used as a constant discharge for a definite period of time with little error being introduced by using the average discharge of the range. All such products can then be accumulated so that relation 5 becomes:

$$\triangle P \propto \frac{\Sigma(Q\,N)}{M} \qquad (6)$$

which is the basis for the analysis of data obtained in this investigation.

The development of relation 6 gives a macroscopic view of the mechanics of meander expansion. This explanation does not take into account the many microscopic processes which take place in a meander, such as bed or bank shear, superelevation, eddy currents, or transverse flow. The contribution of these factors is unquestionable, but they do not always have to be considered in determining direction or magnitude of channel movement. The important consideration is the net effect, and the impulse-momentum concept applied to the concave bank supplies just that. It is a measure of the net effect of flow on an erodible material. The work done (or energy expended) in changing momentum from one value to another is the same no matter what process effects that change.

Channel-Forming Discharge

All discharge within an alluvial channel has some effect on the channel-shape parameters. Because of this it is impossible to relate these parameters to only one discharge. Several investigators have alluded to this premise.

Carlston (1965) found the most significant relationships for meander wavelength to involve average discharge and the mean discharge for the month of maximum discharge. Schumm (1968, 1969) found that when average, bankfull, and mean annual flood discharge are each correlated with the percentage of silt and clay in the channel perimeter and channel properties, the results are, to nearly equal degrees, very significant explanations of meander wavelength and channel cross-sectional properties. Stall and Fok (1968) found that hydraulic geometry was best explained using the discharge at 10-percent flow duration. These relationships show that there is a range of discharge from at least the average to the mean annual flood which controls the dimensions of meanders.

The position of the main-velocity thread in a meander loop at varying discharge has been shown by Friedkin (1945, pl. 9). He indicated that low flow attacks the upstream part of the concave bank, half-bankfull flow attacks the mid-part, and bankfull flow attacks the downstream part. At discharge greater than bankfull, the meandering velocity pattern is not destroyed, and the turbulence effective in erosion may be increased (Toebes and Sooky, 1966).

Channel-Forming Discharge Redefined

Consideration of all the relationships developed indicates not only that all discharge affects channel dimensions, but that there is a threshold discharge at and above which the major part of channel formation occurs. Channel dimensions should depend upon those flows for which the channel acts as a unit. At low flows (less than average), the pool and riffle sequence within channel limits is effective, resulting in a low-water channel which often meanders within the confines of the bankfull channel. At some discharge the pool and riffle sequence is drowned out, and the channel acts as a unit at all higher discharges. The point is probably reached near average discharge as the relationships discussed have indicated.

Some further evidence can be gained from study of traveltime data. Figure 5 presents the results of several traveltime determinations for the East Fork White River. The break in slope occurs near average discharge and is characteristic of unpublished traveltime curves for most of the streams in Indiana which exhibit a pool and riffle condition at low flows.

Channel formation can be considered, then, to begin at just above average discharge and continue

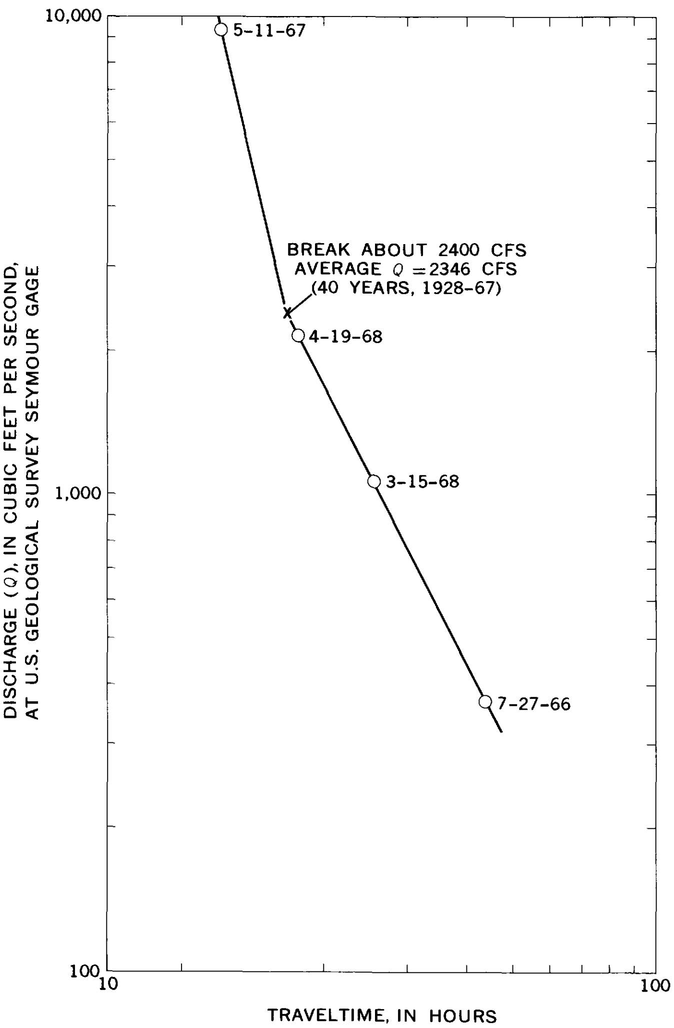

FIGURE 5.—Traveltime for the East Fork White River between U.S. Geological Survey gages at Columbus and Seymour.

for all higher discharges. This range can also be considered to be directly related to the expansion of a meander loop.

The remainder of this paper is an attempt to test the conclusions reached up to this point—namely, that path-length expansion is directly proportional to the volume of flow for above-average discharge days and inversely proportional to the percentage of silt and clay in the bed and bank material.

FIELD INVESTIGATION

STUDY SITES

The sites investigated for this project are shown in figure 6, and some pertinent physical characteristics are listed in table 1. All sites were within a reasonable distance from a U.S. Geological Survey stream-gaging station (fig. 6) except for Paw Paw Creek which is ungaged. As shown in table 1, a wide range of characteristics is represented.

The surficial geologic characteristics were formed during the Wisconsin Glaciation in the Pleistocene Epoch. At the maximum glacial advance, the northern two-thirds of Indiana was covered by Wisconsin ice. The two sites on the White River and the site on the East Fork White River are south of the maximum Wisconsin glacial advance, but the material filling the present river valleys is outwash from the melting of this last continental glaciation. The Muscatatuck River site is also south of the Wisconsin boundary, but the predominately clay material at the site was deposited in a lake whose basin was formed during the previous Illinoian Glaciation. The lake sediments of the Carpenter Creek site and the morainal features of the Paw Paw Creek site were deposited during glacial retreats of the Wisconsin Glaciation.

The weighted silt-clay percentage (fine fraction) was computed by a method described by Schumm (1960), but a diameter of 0.062 mm (millimeter), instead of 0.074 mm, was used as the dividing point

TABLE 1.—*Selected site characteristics*

[Depositional environment: After Wayne (1958)]

Name and location	Drainage area (sq mi)	Period of record (water years)	Average discharge at gaging station (cfs)	Channel slope (ft per ft)	Width-depth ratio	Weighted silt-clay percentage	Depositional environment
Paw Paw Creek near Urbana........	8.60	....	....	0.0018	7.2	7.9	Ground moraine.
Carpenter Creek near Egypt	48.0	1949, 1951, 1953-67	33.7	.00064	8.0	29	Lake sediments.
White River near Martinsville....	2,520	1930-31, 1946-67	2,258	.00035	27	2.2	Valley-train sediments.
White River near Worthington....	4,390	1929-67	4,459	.00023	20	2.6	Do.
East Fork White River near Vallonia	2,530	1928-67	2,346	.00024	14	6.9	Do.
Muscatatuck River near Austin......	367	1933-35, 1937-43	387	.00025	5.8	87	Lake sediments.

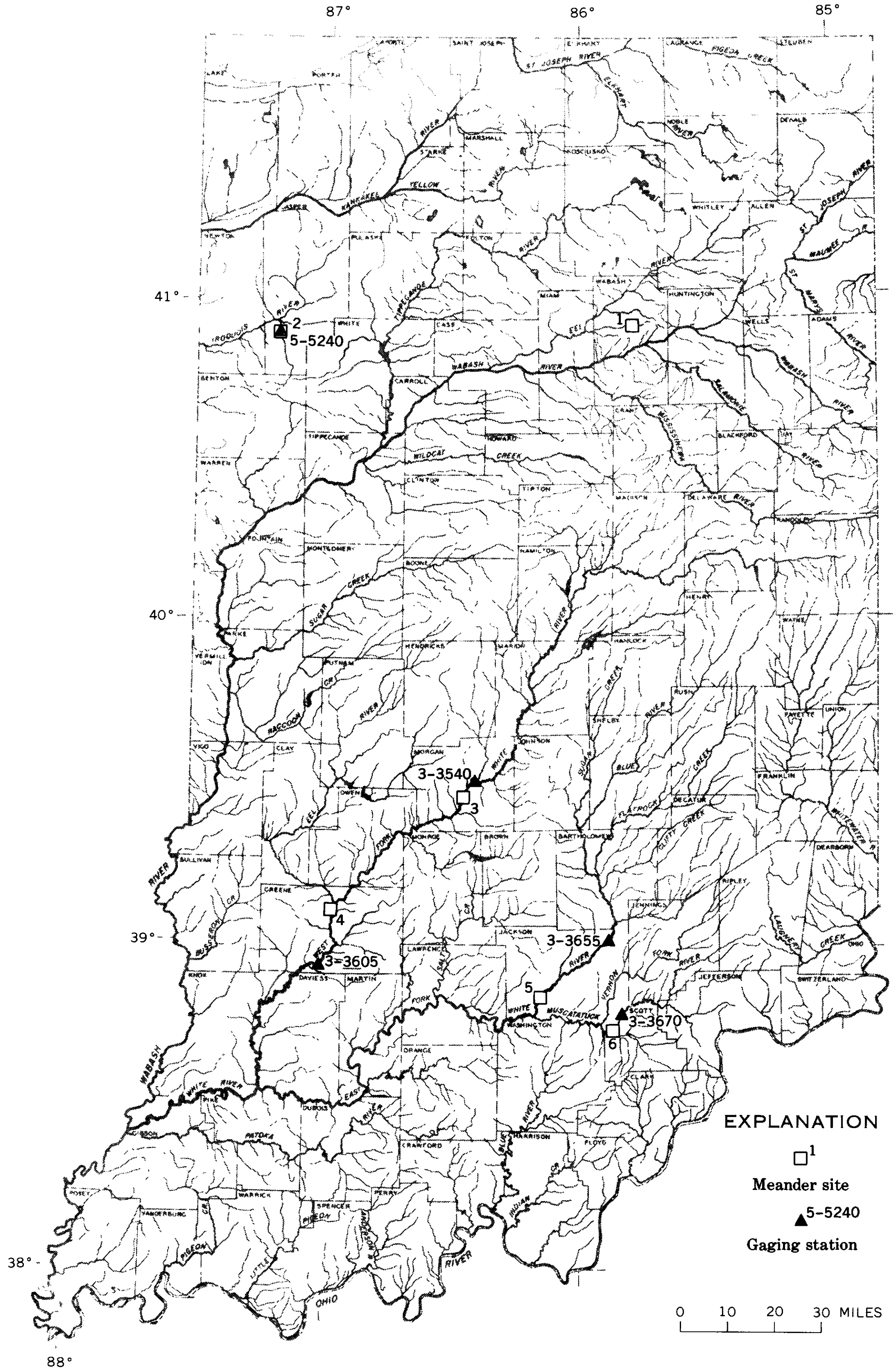

Figure 6.—Location of investigated meander sites and gaging stations.

EXPLANATION FOR FIGURE 6

Meander sites

Map No.	Name and location
1	Paw Paw Creek near Urbana, Wabash County, sec. 12, T. 28 N., R. 6 E.
2	Carpenter Creek near Egypt, Jasper County, sec. 22, T. 28 N., R. 7 W.
3	White River near Martinsville, Morgan County, sec. 7, T. 11 N., R. 1 E.
4	White River near Worthington, Greene County, sec. 28, T. 8 N., R. 5 W.
5	East Fork White River near Vallonia, Jackson County, secs. 19, 30, T. 5 N., R. 4 E.

Meander sites—Continued

Map No.	Name and location
6	Muscatatuck River near Austin, Scott County, secs. 33, 34, T. 4 N., R. 6 E., and sec. 3, T. 3 N., R. 6 E.

Gaging stations

National No.	Name
5-5240	Carpenter Creek at Egypt.
3-3540	White River near Centerton.
3-3605	White River at Newberry.
3-3655	East Fork White River at Seymour.
3-3670	Muscatatuck River near Austin.

for fine and coarse fractions. A dividing-point diameter of 0.062 mm conforms to the Wentworth grade scale and results in only a slightly smaller percentage. The difference is not enough to destroy comparability. Material for these analyses was collected at several locations on both banks within each study reach, and the results were averaged for each reach. The variability within each reach was considered sufficiently small that a reach could be treated as having fairly homogeneous lithology throughout.

The field investigations were carried out from the spring of 1966 to the spring of 1969. Channel locations were identified from aerial photographs and, except for those from 1939 and 1958 for the Martinsville site, were obtained from the files of the Indiana Department of Natural Resources. The two exceptions were obtained from the files of the Soil Conservation Service, U.S. Department of Agriculture. Plan-view channel patterns for all sites are shown in figures 7 through 12. The method of analysis will be illustrated with the White River near Worthington site (fig. 10).

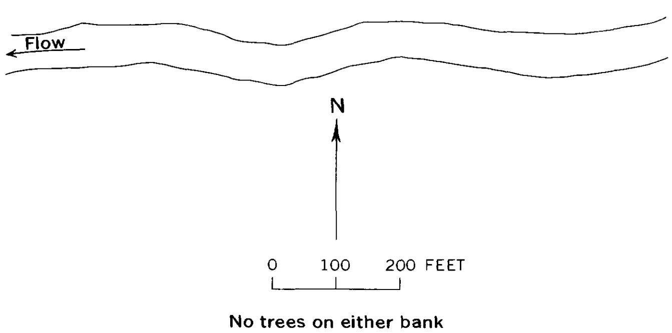

FIGURE 7.—Meander system at the Paw Paw Creek near Urbana site. Surveyed by J. F. Daniel and J. W. Tucker, April 3, 1969.

DATA ANALYSIS

Field surveys at the White River near Worthington site were made June 7, 1966, and July 23, 1968, by Indiana Department of Natural Resources personnel. The results of those surveys and the bank locations based on aerial photographs taken July 5, 1937, and April 16, 1962, are shown in figure 10. Any further usefulness of this site was destroyed when a natural cutoff formed in late June 1968.

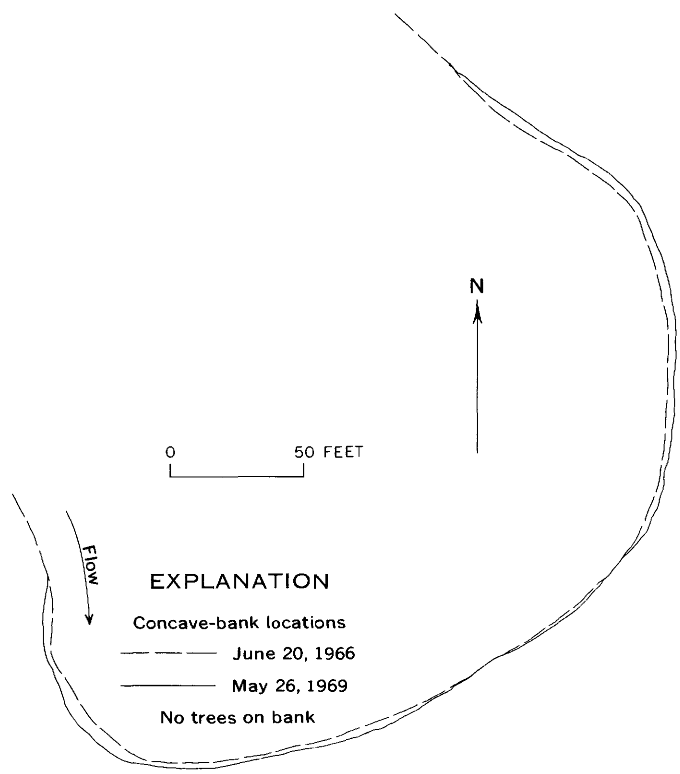

FIGURE 8.—Meander development at the Carpenter Creek near Egypt site. Surveys by J. F. Daniel and others.

Each path location was analyzed independently as follows:

1. The direction angles with an assumed mean downstream direction were measured for equal, short tangents of the cut-bank path length.
2. The direction angles and the stationings were plotted, and a sine curve was fitted to the points. (See fig. 1.)
3. The path length, corrected mean downstream direction (obtained by adjusting the vertical coordinate scale), and amplitude of the sine wave were determined from the graph.
4. The theoretical loop was then compared with the actual loop by plotting the positions of both, beginning at the midpoint stationing of the actual loop.

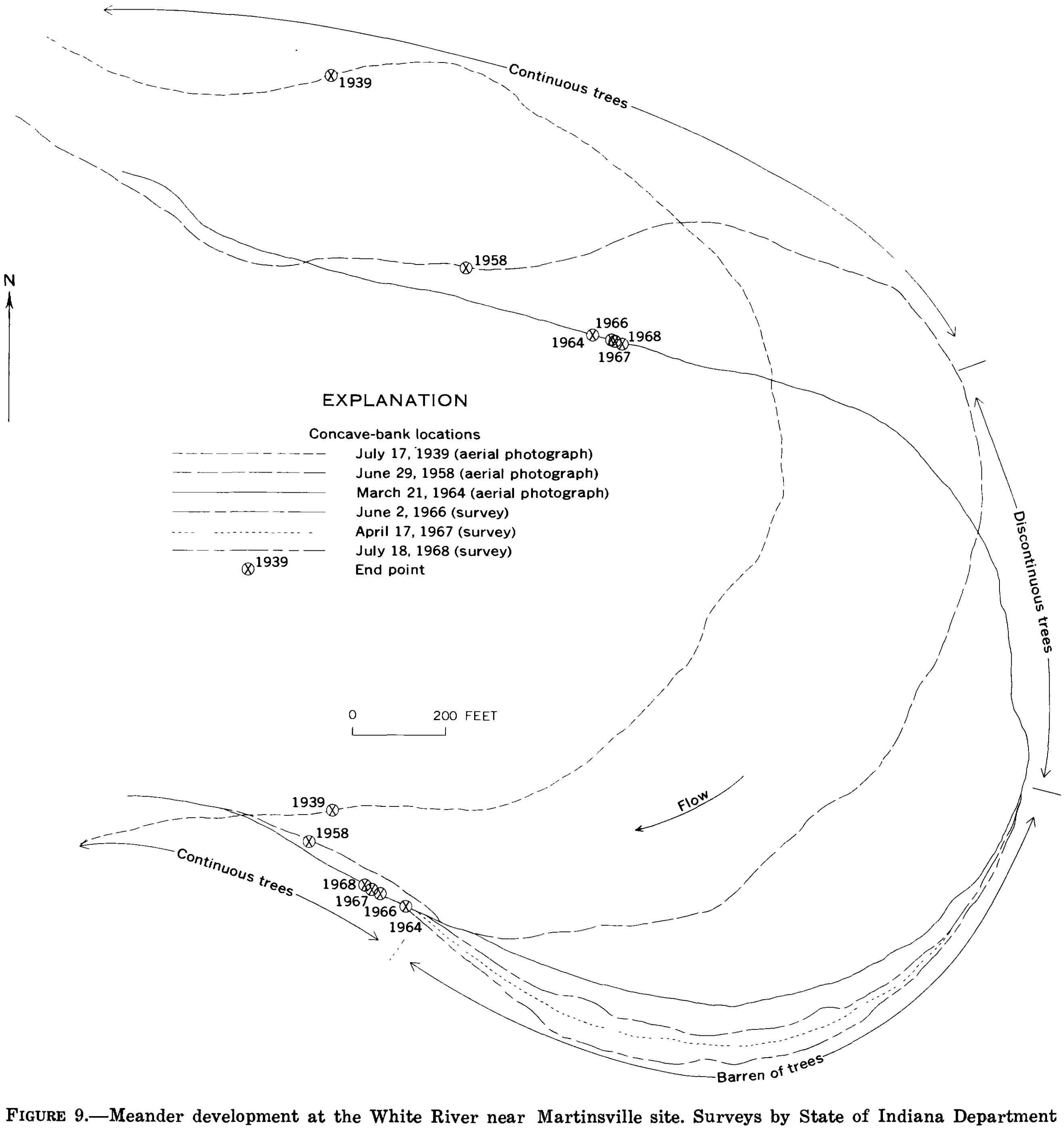

FIGURE 9.—Meander development at the White River near Martinsville site. Surveys by State of Indiana Department of Natural Resources.

5. A line joining the ¼- and ¾-wavelength points on the theoretical loop was extended to the actual loop, as in figure 13. This method objectively defines ¼*P* and ¾*P* on the actual loop, and the path distance between these two points was measured.

Using duration data which were computer-compiled by class interval, the total flow volume of all days having discharge greater than the effective discharge was accumulated. It has already been shown that this effective discharge occurs at a discharge slightly greater than the average. Therefore, accumulation was begun with the first class interval greater than the average. Volume for each class interval was computed by taking the product of the

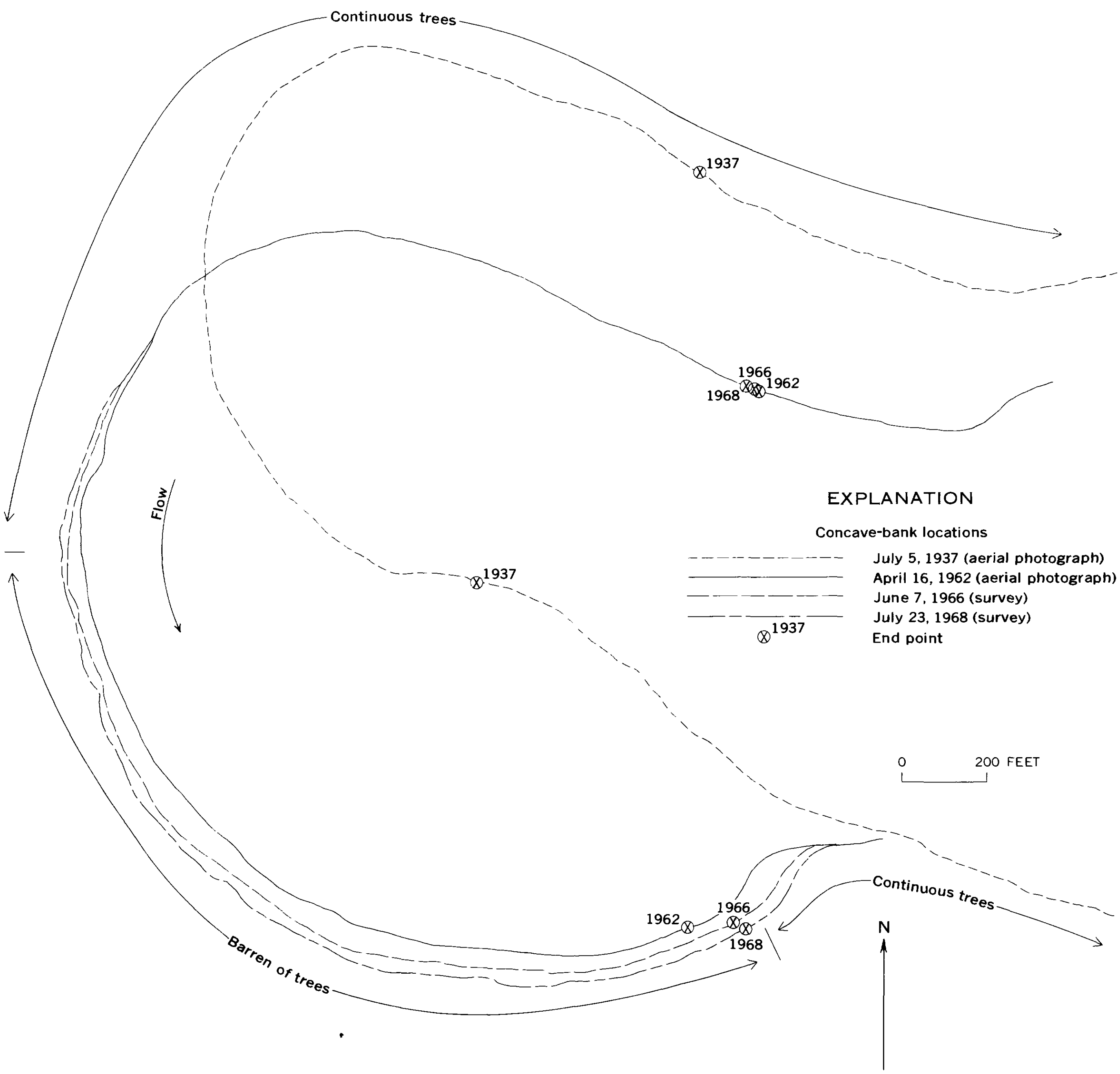

FIGURE 10.—Meander development at the White River near Worthington site. Surveys by State of Indiana Department of Natural Resources.

average of the class and the number of days in the class. While this is not an exact measure, the class intervals are small enough that very little error is introduced.

The effective-discharge volume was then plotted versus the accumulated path-length increase as in figure 14. It appears that the few points available define a straight line, which was fitted by eye. Using the same technique, the same relations were developed for the White River near Martinsville and the East Fork White River near Vallonia sites (figs. 15, 16).

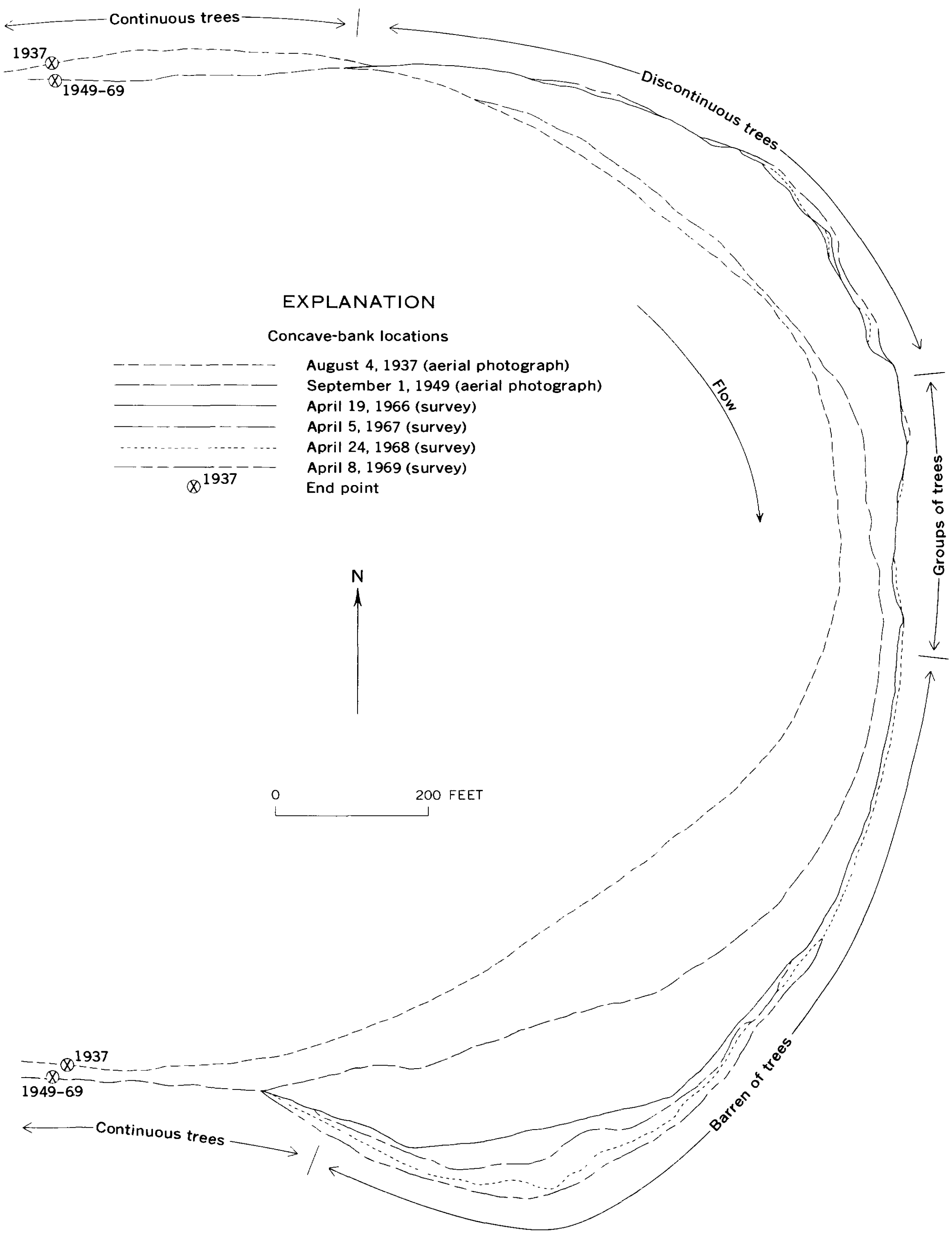

FIGURE 11.—Meander development at the East Fork White River near Vallonia site. Surveys by J. F. Daniel and others.

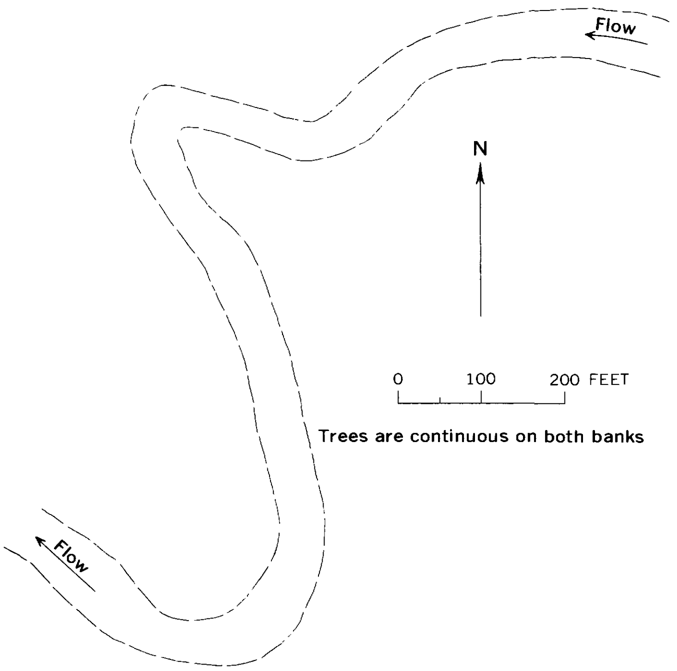

FIGURE 12.—Meander system at the Muscatatuck River near Austin site. Surveys by J. F. Daniel and R. J. Southwood, April 28, 1966.

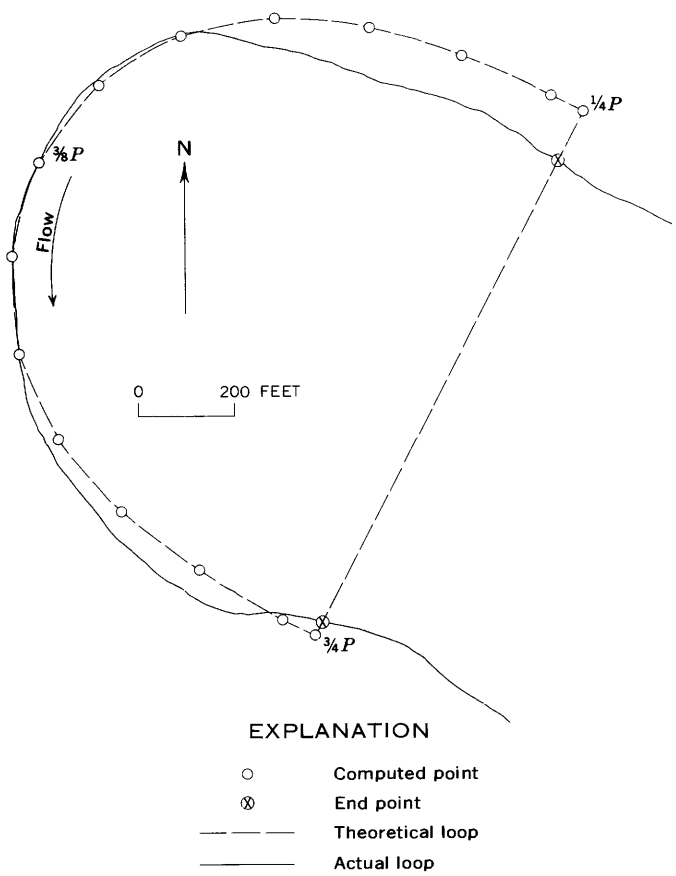

FIGURE 13.—Definition of actual end points from theoretical loop, plotted on 1937 loop, for the White River near Worthington site.

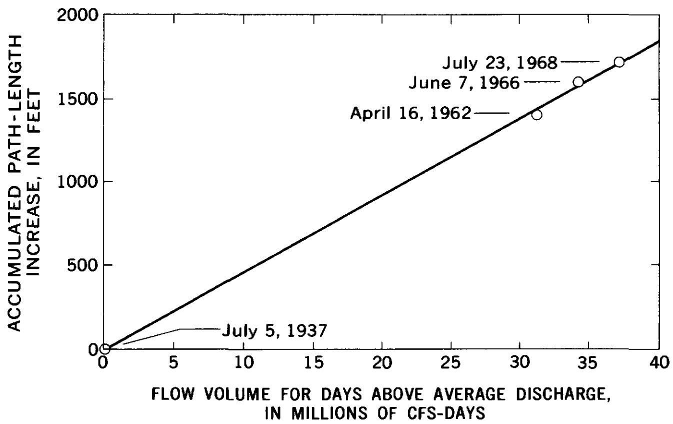

FIGURE 14.—Path-length increase versus flow volume for the White River near Worthington site.

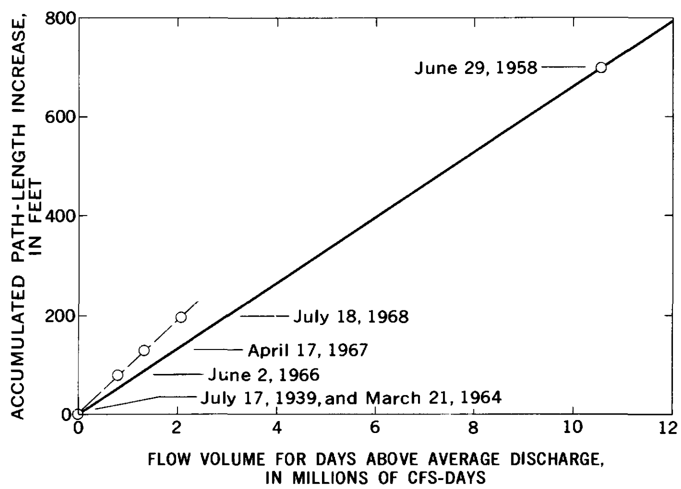

FIGURE 15.—Path-length increase versus flow volume for the White River near Martinsville site.

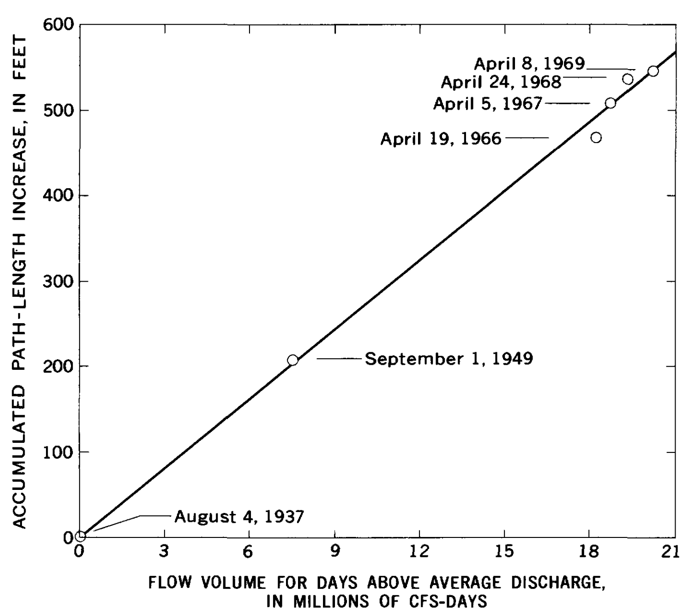

FIGURE 16.—Path-length increase versus flow volume for the East Fork White River near Vallonia site.

INTERPRETIVE DISCUSSION

INDIVIDUAL SITES

The differences between bank locations at different times at the sites on Paw Paw Creek near Urbana, Muscatatuck River near Austin, and Carpenter Creek near Egypt were small; therefore data obtained from studies at these three sites were not adequate for analysis.

Bank locations of Paw Paw Creek for 1941 and 1962, as determined from aerial photographs, are not significantly different from those mapped by surveys in 1967, 1968, and 1969. There is field evidence of erosion and change, as identified by measurements of steel pins set in the channel, but the scale factor of the photographs in combination with such slight changes in bank location makes the data unreliable for developing a mechanism applicable to other sites.

The bank location of the Muscatatuck River near Austin site has not changed during the period 1940–66, as determined from aerial photographs in 1940, 1949, and 1956 and a field survey in 1966. Rotation of steel pins in the channel indicates that bank creep moves earth material toward the bank face where it is loosened by freeze and thaw cycles and carried away by high flows. This indicates that the channel is widening, but at such a slow pace that it is not readily measurable. Another valuable insight learned at this site is that, for this particular relation between silt-clay percentage and discharge volume, the increase of path length is virtually nil.

There was also no significant change at the Carpenter Creek at Egypt site. However, field surveys for a longer period than 1967–69 would probably yield information that would allow analytical results. Aerial photographs for 1939 could not be used to obtain a comparable path because of uncertainty of reference-point location.

The studies at the East Fork White River site yield information which is reliable. The data on expanding path length were collected for a 33-year period when the site was not directly affected by man. The author believes, however, that any further data collection at this site would not be worthwhile because the loop is moving into a prior channel location. Data obtained will no longer be applicable to a singly defined loop.

In conjunction with the field investigation at this site, measurements of daily suspended-sediment load were made at the gaging station upstream. The suspended loads measured during the field-survey period are presented in table 2. Russell F. Flint (written commun., 1966) estimated the average yearly load on the basis of an indirect method of analyzing periodic samples collected during the period 1963-65. Because the daily load record is short and the estimated yearly load seems disproportionately high, no reasonable relation of sediment load to expansion rate has been found. The data herein are presented for future reference.

Some discussion of the White River near Martinsville site is needed to explain the two curves in figure 15. Between 1958 and 1964, the middle part of the loop was stabilized with riprap and the upper part of the loop was apparently straightened. This channel alteration appears to have resulted in an increased rate of path lengthening owing to increased erosion in the downstream part of the loop. It seems likely that this increased rate will be temporary and that there will be a return to the prealteration rate. For this reason the author believes that the previous rate can be used for comparison with rates of other sites.

General relations can be developed from the studies at the Vallonia and Martinsville sites, which were just discussed, and at the Worthington site,

TABLE 2.—*Suspended-sediment loads for East Fork White River at Seymour*

Survey period	Sediment-load period	Sediment load (tons)
4-20-66 to 4- 5-67	7- 1-66 to 4- 5-67	220,705
4- 6-67 to 4-24-68	4- 6-67 to 4-24-68	312,146
4-25-68 to 4- 8-69	4-25-68 to 4- 8-69	971,099
Estimated annual sediment load		721,000

which was used to illustrate methods in the section on data analysis.

GENERAL CONCLUSIONS

Data indicate that for each of the three sites for which analysis was possible a well-defined relationship could be developed between time and path length as well as between discharge and path length. The relation between time and path length is not as sharply defined as that between discharge and path length, but for all practical purposes they are equivalent. The explanation for this is indicated in figure 17 where there is a lack of large deviations between the mass curve and the dashed line. This indicates that annual discharge volumes for days above average discharge are relatively constant. Therefore, an increase in path length would be relatively constant from year to year. This condition is more likely to occur in a subhumid climate, such as that in Indiana, than in a semiarid climate, such as that in the Great Plains, where yearly changes in discharge volume for days above average discharge are relatively much greater. Therefore, while a yearly path-increase rate for the sites in Indiana is sufficient for use, the same method probably could not be used for meander loops developing from different climatological conditions. For streams in different climates, the path-length versus discharge-volume relation should yield better results.

Through the study of the annual path-length increase, some insight can be gained into the effect of grain size. In figure 18 the rate of path-length increase has been transformed to a per-square-mile basis and plotted versus the silt-clay percentage. Not shown is the point defined by the Muscatatuck site (no expansion; 87 percent silt and clay), but it was considered in shaping the curve. Again, while not enough data are available for "proof" of a hypothesis, the points do indicate that the expansion rate would have a nonlinear relation to the silt-clay percentage. It seems reasonable that this relation would be asymptotic to the silt-clay axis, indicating that no bank would completely resist erosion. The extension of the curve toward zero silt and clay may be asymptotic to the rate axis also, but it probably would be discontinuous at some point close to that axis. This would indicate that as the path length increased at an extremely rapid rate the radius of curvature of the channel would become infinite, thereby resulting in a straight reach with little or no

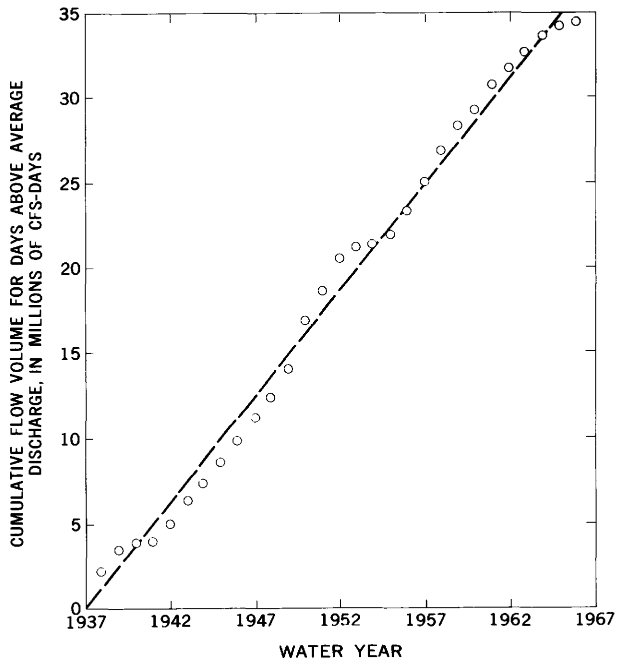

FIGURE 17.—Accumulated flow volume versus water year for White River near Worthington site.

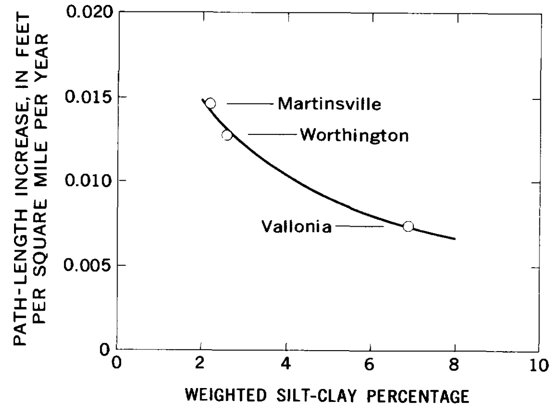

FIGURE 18.—Probable relation of path-length increase and silt-clay percentage.

change in path length. In other words, at some extremely small silt-clay percentage, the path length would not increase. The channel could still move, but the path length would not change except for short periods of time.

In order that comparison with meander migration in other regions can be made in the future, the data have been put into dimensionless form as shown in figure 19. The scatter of the points with regard to silt-clay percentage indicates a lack of

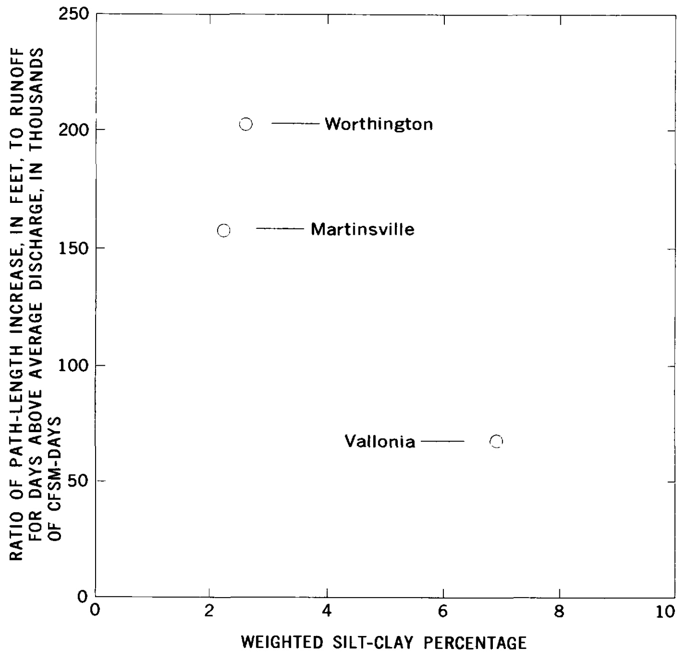

FIGURE 19.—Dimensionless relation of path-length increases and flow data to silt-clay percentage.

orderly progression. However, when width-depth ratio is used as the dimensionless parameter for the abscissa, as in figure 20, a logical sequence of points is obtained.

The apparent discrepancy between these two treatments can best be explained by sampling error. Schumm (1960) related width-depth ratio to silt-clay percentage of the bed and banks. His data were derived from cross sections and indicate a definite correlation between the two parameters. For this investigation several points within each reach were sampled for silt-clay percentage, and the results were averaged for the reach. The scatter of data in figure 19 indicates that enough samples to establish a statistically significant average may not have been obtained. Apparently, then, the average width-depth ratio is a more integrated, and hence better, measure of the average silt-clay percentage than the bed and bank samples themselves.

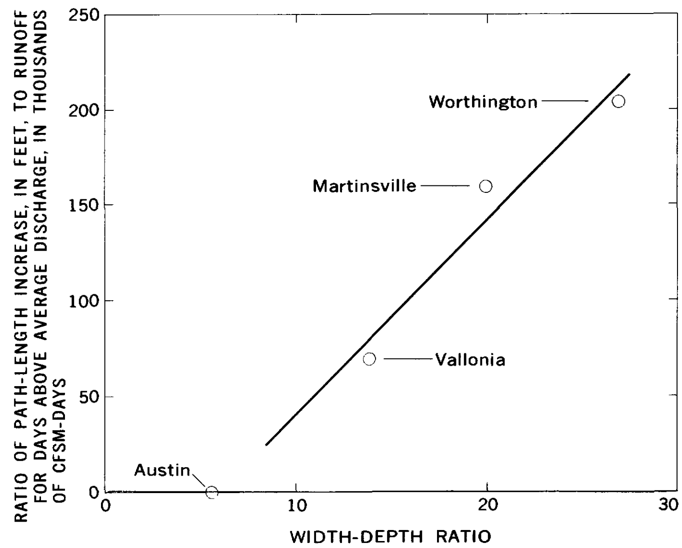

FIGURE 20.—Dimensionless relation of path-length increase and flow data to width-depth ratio.

The interpretation of figure 20 is similar to that of figure 18. The higher the width-depth ratio, the lower is the silt-clay percentage and the faster is the path-length increase. Conversely, the lower the width-depth ratio, the higher is the silt-clay percentage and the slower is the path-length increase. Again, as in the interpretation of figure 18, one would expect that no channel would completely resist erosion so that any curve should pass through the origin. However, because of the few points available, an extension of the curve to the origin has not been shown.

The inclusion of the drainage area in the ordinate may or may not tend to restrict the validity of figure 20 to climatic or geologic conditions similar to those for which it was developed. If it does and if the concept is correct, one would expect to find a family of curves, each representing a particular environment. To test this relation by studying meanders in other areas would seem to be a logical "next step" to this investigation.

The foregoing interpretation of figure 20 tends to invalidate the relation shown in figure 18. Because of this and because of its more usable dimensionless form, the author feels that figure 20 represents the best treatment of the available data. It could be used to estimate path-length increase of alluvial streams in Indiana having width-depth ratios within the approximate range of 8 to 28 and for most flow volumes. Time intervals for path-length increases can be related to flow volume by doing flood-volume frequency analyses for short time intervals or by considering only long intervals (several years) and using average discharge. It must be remembered, however, that path-length increase is only part of the movement mechanism.

The mechanisms of translation and rotation have been described earlier in this paper (figs. 2 and 3) but not enough data are available for a quantitative analysis of the total process. If the end points of a loop are likely to be stable, such as at the Vallonia site, then rotation and translation cease to have an appreciable effect. A useful estimate of movement might then be made with figure 20. Because this condition seldom exists, further investigation of rotation and translation is also a next step to this investigation.

It has also been impossible to evaluate the effects of vegetation on loop expansion. Qualitative descriptions of vegetative cover proposed by Dansereau (1957) and listed by Strahler (1965) have been given on the site illustrations. The percentage of path length supporting dense vegetation is nearly equal for each of the three sites used to develop the relation shown in figure 18. It seems logical that vegetation would slow down expansion. However, unless vegetation covers 100 percent of the path, the experience at the Martinsville site indicates that the effect may be overcome by expansion in that part of the loop which is not protected. The effect of dense vegetation can be likened to the effect of very different material composition; for example, abandoned clay-filled meanders are often the inhibiting factors that control channel movement on the lower Mississippi River (C. R. Kolb, written commun., 1969). Because similar problems in analyzing movement result from either cause, much more data are needed before any quantitative effect of vegetation or very different material zones can be assigned.

SUMMARY

The attempt has been made in this report to review some established principles of channel geomorphology and to use those principles to give some insight to the process and prediction of meander movement.

Meander loop movement has been investigated by using a sine-generated curve to determine the end points of a loop from which the actual path length can be measured. Using the simple physical model of impulse momentum, a relationship of discharge to loop expansion has been deduced and related to grain size of the bank material.

Consideration of traveltime data and the regression analyses of many other investigators has led to the conclusion that channel-forming discharge begins very near, but just higher than, average discharge and continues throughout all higher discharges. Channel movement is then a function of the time distribution of the higher discharges.

A division of the channel material into fine and coarse fractions has been used in order to relate the rate of expansion to the cohesiveness of the banks. Suspended-sediment discharge records were collected for one site but are not of sufficient length for rigorous analysis.

Several simple models of channel movement by rotation, translation, and expansion have been illustrated on the basis of the experience gained from this investigation. No general relation has been found with which the first two processes could be analyzed. Therefore, the goal of movement prediction has not been achieved. However, if reasonable relationships can be found to relate rotation and translation to common factors, those relationships, along with the expansion relation which has been defined, will give scientists a tool with which it may be possible to predict the movement of meanders.

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